

MAGNETIC FLOODS: A SCENARIO FOR THE VARIABILITY OF THE MICROQUASAR GRS 1915+105

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ABSTRACT

We present a scenario for the variability of the microquasar GRS 1915+105. This starts from previous works, leading to the tentative identification of the Accretion-Ejection Instability as the source of the low-frequency Quasi-Periodic Oscillation of microquasars and other accreting sources. We follow the physics of this instability: its conditions (the magnetic field and geometry adapted to MHD jet models), its instability criterion, and its consequences (cooling down of the disk, heating and excitation of the corona). Comparing them to the observed properties of the source, in particular the detailed properties of its spectral states, we first derive a model for the ~ 30 minutes cycles often exhibited by GRS 1915+105. In our model this is a limit cycle determined by the advection of poloidal magnetic flux to the inner region of the disk, and its destruction by reconnection (leading to relativistic ejections) with the magnetic flux trapped in the vicinity of the central source. We show how it leads to natural explanations for observed behaviors of GRS 1915+105, including the three basic states of Belloni *et al.* (2000). We then discuss how this could be extrapolated further to understand the longer-term variability of this and other microquasars.

Subject headings: MHD — accretion, accretion disks — X-rays: stars — stars: individual (GRS 1915+105)

1. INTRODUCTION

Since they were observed in X-ray binaries, Quasi-Periodic Oscillations (QPO) have been considered as an important clue to the physics of the inner region of accretion disks, at a few tens to hundreds of kilometers from the central source (a white dwarf, a neutron star or a black hole). Their frequencies, typical of keplerian rotation in this region, and their RMS amplitude (typically a few %, up to a few tens of %, of the total luminosity), as well as a number of other elements, tend to indicate that they are associated with high magnitude phenomena occurring in the disk, and possibly at the base of the jet. However no model has yet gained general acceptance to explain any of the QPO, or given indications for a more general explanation of the accretion process.

We have in the last few years presented the Accretion-Ejection Instability (AEI: Tagger and Pellat (1999)) and shown that its properties make it a very promising explanation for the low-frequency (~ 1 -10 Hz) QPO (hereafter LFQPO), prominent in black-hole binaries and also present in certain states of those hosting a neutron star or a white dwarf. The goal of this paper is to present a model which was elaborated gradually, since the discovery of the

AEI; earlier versions of this model were presented in Tagger (2000) and Tagger (2002). It starts from the tentative identification of the AEI as the source of the QPO, and extrapolates by seeking in the properties of the instability an explanation for the observed behavior of the most spectacular microquasar, GRS 1915+105.

Since its discovery (Castro-Tirado *et al.* 1992, 1994), soon followed by the observation of massive superluminal ejections (Mirabel and Rodriguez 1994), this source has been the object of a large number of observations, from X-rays (mostly by the Rossby X-ray Timing Explorer, RXTE), to radio and IR. They have characterized it as the most permanently active black-hole binary, showing a large variety of temporal and spectral behaviors. This occurs at all time scales: high and low-frequency QPOs, but also repetitive patterns of behaviors during typically minutes or tens of minutes, a very long and steady ‘plateau’ state, etc. Belloni *et al.* (2000) have given a classification of these modes of variability, showing that they fall into twelve distinctive classes which again can be reduced to oscillations between three basic states. These behaviors are so well characterized and so well observed at all wavelengths (including their connection with both a compact jet and relativistic

¹Deceased August 4, 2003.

ejections) that they are widely expected to contain clues to the accretion and ejection processes in all types of accreting sources, from young stars to X-ray binaries and AGN. We will discuss this in more details in sections 3 and 4.5, and clearly we expect that our model will be found relevant to other accreting sources.

In particular in this paper we concentrate on the cycles where, with a periodicity of the order of 30 minutes, GRS 1915+105 alternates between a high/soft and a low/hard state, and produces relativistic ejections. As shown by Belloni *et al.* (2000), this cycle is the most frequent type of variability observed in this source besides a steady hard state. Our ‘Magnetic Flood’ model owes its name to the fact that we are led, in our extrapolation process, to believe that these cycles, and maybe the longer-term behaviour of GRS 1915+105, are controlled by the accumulation and release of poloidal magnetic flux in the innermost region of the accretion disk.

In this sense our scenario has much in common with the model of Livio *et al.* (2003), who propose that accreting sources switch between two states, controlled by the global poloidal magnetic field. This follows in particular the work of Merloni (2003), who finds that the low-hard state of GRS 1915+105 can be fitted by assuming that a substantial fraction f of the accretion energy is emitted to the corona and jet rather than heating the disk. Our work is different in that we start from a definite physical model of accretion in the disk, due to the AEI, and build up on that. This leads to a number of differences, *e.g.* as will be seen in section 4.3 in the nature of state *A* as defined by Belloni *et al.* (2000).

Beyond the identification of the AEI as the source of the LFQPO, our model is built by extrapolation, and does not rest on precise arguments, such as predictions or numerical values. It only claims to be a possible explanation for the observed behaviors, obtained by following the most straightforward line of deductions. On the other hand, as will be seen in this paper, we find it already useful in guiding us as we seek new diagnostics of the disk physics. It is however encouraging that, since it was first proposed, we have found it compatible with new elements gathered in the observations, and that we obtain with it possible explanations for puzzling observations, such as the transitions between Belloni’s states (Belloni *et al.* 2000).

The paper is organized as follows: in section 2, so that this paper is reasonably self-contained, we review theoretical and numerical results on the AEI and its main properties. Section 3 is dedicated to a short review of the variability of GRS 1915+105, from the time scale of the QPO to that of the ~ 30 minutes cycles and to properties observed on much longer periods. Section 4 will present our model, and section 5 our conclusions.

2. THE ACCRETION-EJECTION INSTABILITY

2.1. Basic theory

The Accretion-Ejection Instability (Tagger and Pellat 1999) is a global mode occurring in magnetized disks threaded by a poloidal (vertical) magnetic field, *i.e.* the geometry used in MHD jet models. It belongs to the same family as the spiral instability of self-gravitating disks,

and the Papaloizou-Pringle instability (hereafter PPI) of unmagnetized, non-self-gravitating ones. It can also be viewed as the p-mode of diskoseismology models (Nowak and Wagoner 1991), modified by magnetic stresses; the big difference here is that as in galaxies (though less violently) this mode is *linearly unstable*, so that it does not rely on other mechanisms to reach the high amplitudes necessary to explain the LFQPO.

The global structure of these modes is formed by spiral waves travelling back and forth between the inner disk edge (or its center) and their corotation radius², where their angular phase velocity is equal to that of the gas or stars. The mode frequency is typically (depending on the profiles of various quantities) .1 to .3 times the rotation frequency of the gas at the inner disk edge, placing the corotation radius at ~ 2.5 to 4 times the inner radius. It is most unstable when the magnetic field is near equipartition, *i.e.* when the plasma $\beta = 8\pi p/B^2$ (the ratio of thermal to magnetic pressure) is of the order of 1, and requires that the radial gradient of the magnetic field be sufficient:

$$\frac{d}{d \ln r} \ln \left(\frac{\kappa^2}{2\Omega} \frac{\Sigma}{B^2} \right) > 0 \quad (1)$$

where κ and Ω are the epicyclic and rotation frequencies (with $\kappa = \Omega$ in a keplerian disk), Σ is the surface density of the disk, and B the equilibrium magnetic field. It is noteworthy³ that this condition is always fulfilled in self-similar MHD models of jets (Blandford and Payne (1982), Lovelace (1986), Pelletier and Pudritz (1992)).

The restricted radial extension, and the condition that $\beta \sim 1$, make the AEI a complement to the Magneto-Rotational Instability (MRI) of Balbus and Hawley (1991). The MRI is a *local* instability (although modes are also possible, see Curry and Pudritz (1998)), and thus can occur throughout a sufficiently ionized disk. On the other hand it is restricted to weakly magnetized disks, *i.e.* with $\beta > 1$.

Figure 1 shows a schematic description of the mode structure in and above the disk. The spirals are density waves, *i.e.* sound waves whose propagation is modified by differential rotation, by the Coriolis force (resulting in epicyclic motion) and, if they apply, by self-gravity and the Lorentz force. They become unstable by extracting energy and angular momentum from the inner region of the disk (thus causing accretion) and finding a way to transfer them outward: either (this is known as the swing mechanism) to another spiral wave, traveling outward beyond corotation; or (by the corotation resonance) to a Rossby wave at the corotation radius: this is the main amplification mechanism for the AEI.

The AEI owes the ‘E’ in its name to a unique characteristic: as mentioned above, it grows by extracting energy and momentum from the disk and transferring them to a Rossby vortex. In a purely hydrodynamical or self-gravitating disk the process stops there, and this led Narayan *et al.* (1987) to speculate, in the case of the PPI, that the corotation resonance might saturate non-linearly when no more angular momentum can be absorbed at

²not to be confused with the radius of corotation with the central object

³J. Ferreira, private communication

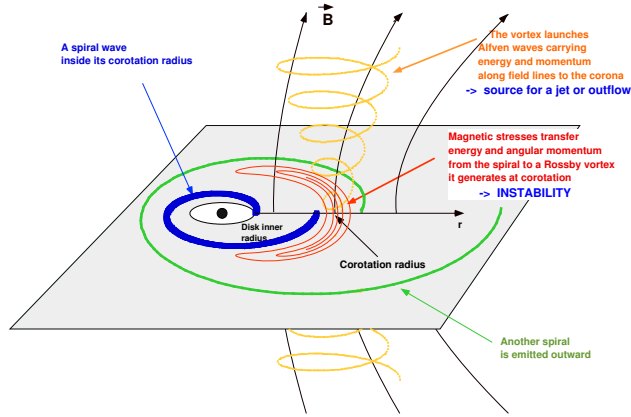


FIG. 1.— A schematic description of the structure of the AEI in the disk and corona. As other spiral modes (self-gravitating galactic disks, Papaloizou-Pringle instability) it is formed essentially by spiral waves traveling back and forth between the inner disk edge (or the galactic center) and the corotation radius, where the waves rotate at the same speed as the gas. The AEI mode is mainly amplified by coupling to a Rossby vortex it generates at the corotation radius, and transferring to it the energy and angular momentum it extracts from the disk. In a disk threaded by a poloidal magnetic field, the torsion associated with the vortex propagates along the field lines as Alfvén waves, carrying to the corona a substantial fraction of the accretion energy extracted by the spiral from the disk.

corotation. However the AEI applies to disks threaded by a poloidal field. Thus the footpoints of the magnetic field lines anchored in the disk are submitted to a twisting motion by the vortex, and this twist can now be propagated along the field lines as Alfvén waves. It was suggested by Tagger and Pellat (1999), and proven by Varnière and Tagger (2002), that these Alfvén waves could carry to the corona of the disk a substantial fraction of the energy and momentum extracted by the instability. This contrasts with all other disk instability mechanisms, or with the turbulent viscosity model of Shakura and Sunyaev (1973), where the energy and momentum are transported *radially* outward and would need an additional mechanism to be redirected upward. This gives the AEI the potential to directly feed the winds or jets observed in all types of accreting sources.

Note however that, at the present stage of theoretical work, we have only shown that the energy and momentum are emitted upward as Alfvén waves. There remains to show how these waves can deposit their energy in the corona, to really produce a jet. Work in progress already allows us to show how the instability can *heat* the corona, thus permitting the Inverse Compton effect for the high-energy tail of the source spectrum.

Theory shows (Tagger *et al.* 1992) that, as for galactic spirals, the structure of the AEI is essentially constant across the disk thickness. Caunt and Tagger (2001) have used this property to perform numerical simulations, similar to early simulations of disk galaxies, considering an infinitely thin disk in vacuum. The drawback is that these simulations can describe neither the MRI (which develops within the disk thickness) nor the coupling of the AEI with Alfvén waves in the corona. But their relative simplicity allows very long simulations (tens of rotation periods), necessary to show the full non-linear development of the instability. These simulations are in very good agreement with the theoretical predictions.

Our identification of the AEI as a candidate to explain the QPO starts from its frequency, and relies on various other elements:

- The frequency of the AEI for the 1-armed mode (usually the most unstable) is typically .1 to .3 times the keplerian rotation frequency at the inner edge of the disk, Ω_{int} . This is consistent with the observed frequency of the LFQPO (typically in the range 1-10 Hz in black-hole binaries) and the inner radius given by spectral fits. They are observed to be correlated in GRS 1915+105 (Muno *et al.* 1999). Furthermore Psaltis *et al.* (1999) have found that, across a large number of sources of various types, the QPO frequency is correlated with a higher-frequency QPO believed to be of the order of Ω_{int} .
- The AEI is an instability, *i.e.* it grows spontaneously and does not need an external excitation, or the formation and long-term survival of blobs of gas, to reach a large amplitude. Furthermore, and by analogy with galactic spirals, we expect it to form a long-lived, near-steady-state feature, described in the galactic context as a Quasi-Stationary Spiral Structure - and indeed this is what we observe in our simulations. This gives it a clear potential to yield the observed Quasi-Periodic Oscillations.
- The LFQPO is so frequent in the ‘low-hard’ state of black-hole binaries that it has been dubbed the ‘ubiquitous QPO’ (Markwardt *et al.* 1999). For a detailed overview of the QPO properties in GRS 1915+105, see Muno *et al.* (1999), Reig *et al.* (2000), Tomsick and Kaaret (2001). In the most common spectral analysis of the X-ray emission of these sources, as a multitemperature black body from the disk and a power-law tail from inverse Compton emission in the corona, this state is characterized by a weak or inexistent disk emission, and a dominant coronal one. This is to be expected from the AEI, since one of its characteristics is that

the accretion energy is transported away by waves rather than dissipated locally to heat the disk, as assumed in the standard model of turbulent viscosity (Shakura and Sunyaev 1973). Thus at comparable accretion rates the AEI should give a lower disk emission and a more active corona than other instability mechanisms. In the course of the work discussed below, where we considered relativistic effects, we found possible evidence for this. We showed that, at the transition between the high and the low state, during a ~ 30 minutes cycle of GRS 1915+105, the QPO appeared just *before* the spectral transition (Rodriguez *et al.* 2002a): as shown in figure 7 of that paper, while the count rate decreases smoothly, the transition is marked by a sudden drop of the color temperature, which in one case is seen clearly to occur around 30 seconds after the apparition of the QPO. Although it is presently limited to one observation, this means that, if there is a causal relation between the QPO and the transition to the low state, it is opposite to the one usually assumed: it is *the apparition of the QPO* which causes the transition, by stopping the heating of the disk and sending energy to its corona.

- In Varnière *et al.* (2002) and Rodriguez *et al.* (2002a) we have given a possible explanation for the observation, by Sobczak *et al.* (2000), that in the microquasar GRO J1655-40 the correlation between the color radius (taken as an indication of the disk inner radius r_{int}) and the LFQPO frequency was opposite to the one usually found. Our interpretation is based on the sensitivity of the AEI to relativistic effects on the rotation curve, when the inner disk edge approaches the Last Stable Orbit. It can of course be taken only as tentative, given the uncertainties in fitting the observed emission with a standard model of a multitemperature black body plus a power law. It is however remarkable, given these uncertainties, that our best fits indicate black-hole mass in agreement with independent measurements.
- As a by-product of our analysis of GRO J1655-40 we also discussed how, when spectral fits give an anomalously low value for r_{int} (sometimes smaller than the Schwarzschild radius of the black hole), and if one retains the analysis in terms of a multicolor black-body contribution to the spectrum, this indicates emission from a small area at high temperature. It might thus correspond to a hot spot, at the spiral shock resulting from the AEI in the disk. Rodriguez *et al.* (2002b) found possible evidence for this in GRS 1915+105, by a determination of the energy spectrum of the QPO at high energies.

3. THE VARIABILITY OF GRS 1915+105

Belloni *et al.* (2000) have shown that the variability of GRS 1915+105 could be reduced to 12 basic classes (noted by greek letters), which again could be analyzed as successions of three basic states, *A*, *B* and *C*. They also found

that, after a steady hard class (noted χ), the most frequent one was class β , marked by the ~ 30 minutes cycles we are interested in. These cycles, a typical example of which is shown in figure 2 (Mirabel *et al.* 1998; Chaty 1998), have been the object of multi-wavelength observations which contain a large number of informations. X rays show first a high and soft state (until time 8.1 in figure 2), then a rapid transition to a low and hard state; at time 8.23 an intermediate spike occurs, also marked by a sudden drop in the high energy ('coronal') emission. The low-energy ('disk') emission keeps recovering until time 8.33, where the source transits back to the high state. IR and radio observations show a strong emission, after some delay which is consistent with synchrotron emission from an adiabatically expanding blob ejected at or near the intermediate spike. Eikenberry *et al.* (1998) analyze more such cycles, confirming this association between the spike and the blob ejection. More details can be found in Fender *et al.* (1997), Mirabel *et al.* (1998), Fender and Pooley (1999), Dhawan *et al.* (2001).

Markwardt *et al.* (1999) performed a detailed timing analysis of the same X-ray data. They found that the low-frequency QPO was prominent, from the transition to the low state until the spike. From spectral fits they found that the inner disk radius r_{int} was near a minimal value at the transition to the low state; it then increased progressively to a maximum and decreased again until, just before the spike, it was back to its minimal value. During the same period of time the QPO frequency started from a maximal value, decreased and then grew again, with variations opposite those of r_{int} . Since this particular observation had been intensively analyzed and discussed, it is the one we chose to analyze in our more recent work (Rodriguez *et al.* 2002a).

The longer-term variability of GRS 1915+105 is more of a puzzle, as it exhibits the 12 classes described by Belloni *et al.* (2000). We will return to this in section 4.5.

4. MAGNETIC FLOODS

4.1. The transition to the low state

Our Magnetic Flood scenario starts from the assumption, following the discussion in section 2.2, that the AEI is indeed at the origin of the QPO; we then wonder what this may tell us about the physics of the inner region of the disk, and seek in the properties of the AEI an explanation for the observations discussed in section 3. As already mentioned, the low state associated with the QPO can be understood in this context since the AEI transports the accretion energy by spiral waves, rather than depositing it locally to heat the disk.

Let us now consider what can explain the apparition of the QPO. It should mean that an instability threshold is crossed: either the radial profiles have evolved so that condition (1) becomes true, or the plasma β becomes of the order of 1. We prefer the second hypothesis for two reasons:

- (i) The power density spectrum (PDS) of the source changes radically at the transition: it is close to a power-law in the high state (see *e.g.* Reig *et al.* (2003)), while in the low state it shows broad-band noise at low frequencies, with a break just below the QPO frequency. In the high state,

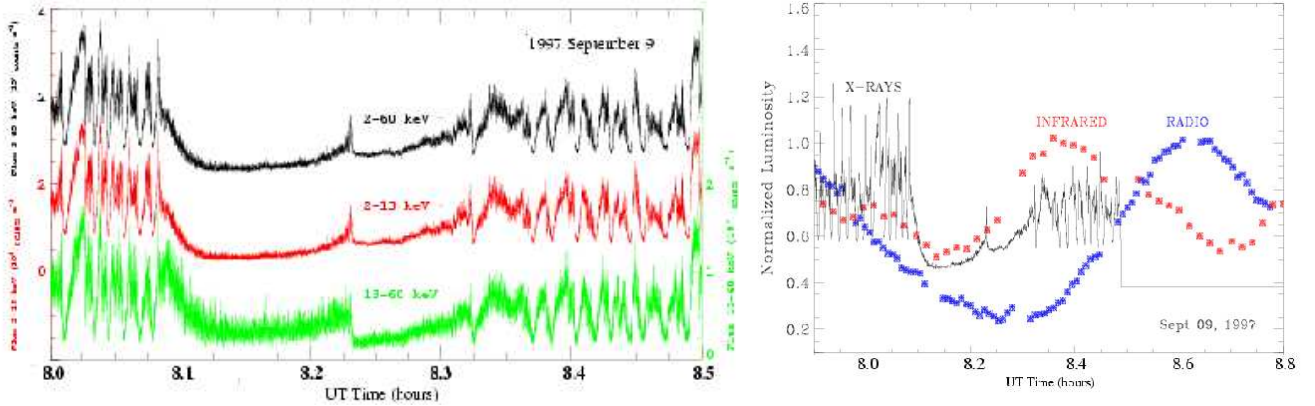


FIG. 2.— A cycle (β state of Belloni *et al.* (2000)) of GRS 1915+105, observed on Sept. 9, 1997 (Mirabel *et al.* 1998; Chaty 1998). Top: the X-ray emission in various bands. Bottom: total X-ray (black), IR (red) and radio (green) emissions.

we assume that turbulence in the disk is due to the Magneto-Rotational Instability (MRI) of Balbus and Hawley (1991), which is not sensitive to the radial profiles but precisely has the property to be suppressed when $\beta \leq 1$. This suppression would explain that, besides the apparition of the LFQPO, the PDS (which we associate with turbulence in the disk) changes so strongly at the transition.

- (ii) Furthermore this would explain that the transition to the low state is so sharp, since as soon as the AEI appears the disk cools down, further reducing the gas pressure and thus β .

A gradual reduction of β during the high state thus becomes our working hypothesis. Two reasons can explain it:

Advection: When considering the magnetic field in a disk, one should distinguish between the ‘horizontal’ and ‘vertical’ (*i.e.* parallel and perpendicular to the disk plane) components of the magnetic flux. The horizontal (azimuthal and radial) flux can easily change, *e.g.* when a horizontal flux tube is lifted by buoyancy and leaves the disk (this is the elementary mechanism of the Parker instability), or when horizontal flux is generated by a turbulent dynamo. Lifting a vertical flux tube, on the other hand, will not change the total flux threading the disk. The only way to do this is, either by reconnection with the magnetic structure in the inner hole surrounding the central object (this will be discussed in section 4.4); or by letting the vertical flux diffuse radially outward against the accretion flow, which may not be an easy process, with advection competing against the turbulent magnetic diffusivity.

Dynamo: The second possibility is that of a turbulent dynamo, associated with the MRI, which would create vertical flux of opposite polarities in the inner and outer disk regions.

These possibilities ultimately depend on the transport properties of the MRI; at this stage, numerical simulations

have not been able to give clear conclusions about the radial transport of vertical magnetic flux by the MRI, *i.e.* a turbulent magnetic diffusivity together with a turbulent viscosity. Dynamo action has been observed by Brandenburg *et al.* (1995) but not yet fully characterized. On the other hand, the MRI is linearly an ideal MHD instability, and as such should cause accretion of the magnetic flux *together* with the gas. Magnetic diffusivity is involved in the non-linear evolution of the MRI, and should break this property. To get an answer on this, we may have to wait for more complex simulations, permitting in particular the magnetic flux to cross freely the boundaries of the computational domain. Or we could find an indication in the observation of strong magnetic fields in the inner few tens of parsecs of the Milky Way: there the field is vertical and measured in milligauss, rather than horizontal and measured in microgauss elsewhere in the disk. Chandran *et al.* (1998) have argued that this may be fossil magnetic flux, advected with the gas during the history of the Galaxy. Thus further studies are needed to assess the fraction of its embedded magnetic flux the gas is able to transport inward. Whatever the result, that fraction will accumulate near the central object and we consider it as very likely that this will cause β to gradually decrease in the inner region of the disk. A final argument for this is that MHD models of jets (Blandford and Payne (1982), Lovelace (1986), see Casse and Ferreira (2000) and references therein) all require an ‘hourglass’ magnetic geometry, *i.e.* vertical flux threading the disk, and $\beta \sim 1$. These are axisymmetric equilibrium models, which as mentioned previously are unstable to the AEI. Our work can thus be considered as an elaboration on this line of models, assuming that turbulence in the disk self-consistently generates this configuration.

We also note that the accretion of gas can noticeably change the mass of the central object only on a very long term. The same applies to the magnetic flux of a neutron star. On the other hand the magnetic flux threading a black hole is not anchored in the black hole, but is due to currents near the inner edge of the disk. A secular evolution of this flux may thus have a much stronger effect on the disk behavior.

4.2. The low/hard state

Following our scenario, in the low state the AEI transports the accretion energy outward to its corotation radius; a sizable fraction of it can then be transported to the corona, as shown by Varnière and Tagger (2002), so that the disk cools down and the corona becomes more active. The rest of the energy is dissipated in the disk at a spiral shock, forming a hot spot as shown by the numerical simulations of Caunt and Tagger (2001); indications for such a hot spot, associated with the QPO in GRS 1915+105, have been discussed by Rodriguez *et al.* (2002b).

From the transition to the low state, the inner radius of the disk is observed to move gradually outward; this may be the result of the equilibrium between the standard, optically thick disk and whatever lies between it and the black hole: a radiatively inefficient disk, *e.g.* an ADAF (in which case the inner radius of the optically thick disk we are concerned with is set by the conditions of transition to the ADAF), or *e.g.* the force-free magnetic structure associated with the Blandford and Znajek (1977) process, formed by a current ring at the inner edge of the disk. In that case the change in r_{int} would be set by the MHD equilibrium between this structure and the disk, whose pressure has changed at the transition.

Then after some time r_{int} is observed to decrease again, until it returns to the minimal value observed in the high state. This may be attributed to the viscous refilling of the disk, as indicated by the correlation (Belloni *et al.* 1997) between the maximal value reached by r_{int} (during this or other types of events) and the time it takes to return to its minimal value. During this evolution the QPO frequency first decreases, then increases, leaving its ratio to the keplerian frequency at r_{int} in the range predicted by the AEI.

The low-hard state stops when r_{int} has returned to near its minimal value, which it is of course tempting to identify with the Last Stable Orbit (LSO). This is when the intermediate spike occurs, presumably causing the relativistic ejections. Eikenberry and Van Putten (2003) show that this is consistent with a reconnection event. We will not discuss here their ‘Magnetic Bomb’ model, which involves a specific configuration for the central magnetic structure connecting the black hole with the inner edge of the disk. Whatever this configuration is, reconnection should cause the ejection of a large part of the corona, as seen in figure 2 where after the spike the hard X-ray flux has significantly dropped, which may indicate the ejection of part of the corona (Chaty 1998).

Reconnection destroys magnetic flux: this will allow the disk to return to a state of low magnetization, and thus to a high state. However this does not occur right away, and we should also seek an explanation for this delay, which extends from the spike to time $\simeq 8.32$ in figure 2.

4.3. Belloni’s states

The answer might lie in the work of Belloni *et al.* (2000), who have shown that the twelve classes of variability of GRS 1915+105 they had identified could be reduced to alternances between three basic states, labelled *A*, *B* and *C*, identified by the position of the source in a color-color diagram. This allows a much more detailed view of the evolution of the source. State *B* is a conventional high-

soft state, with strong disk emission and weak coronal one; state *C* is a low-hard state, with weak disk and relatively strong corona (high hardness ratio), while state *A* is characterized by low emission in all bands. The LFQPO is seen only in state *C*. The ‘high state’ during the cycles turns out, once analyzed on very short time scales, to be actually a succession of these three basic states, while the ‘low state’ is *C* and after the spike the source is in state *A*.

Following our line of inferences, we assume that state *C* is subject to the AEI: the inner region of the disk must thus be moderately magnetized with $\beta \lesssim 1$, and obey the instability condition (equation 1). The cool disk and active corona, as well as the presence of the compact jet (see *e.g.* Reig *et al.* (2003)), are consistent with the presence of the AEI.

It is also natural to consider state *B* as a weakly magnetized ($\beta > 1$) state subject to the MRI, which is our best candidate to produce turbulence leading to a local heating of the disk by the accretion energy (whether or not the effects of the MRI can be modeled by a standard α disk: see *e.g.* Balbus and Hawley (1998)).

We still have to understand in this context the nature of state *A*. It cannot be a state where the inner region of the disk is weakly magnetized, since it would be subject to the MRI whatever the other disk parameters are, and should thus show properties similar to state *B*. It must thus have $\beta \leq 1$, and be stable to the AEI: this can occur if the instability criterion of equation 1 is not verified, *i.e.* if the quantity B^2/Σ does not decrease faster than Ω outward. The association of the spike with a reconnection event makes this a very likely possibility: reconnection, destroying magnetic flux at the inner disk edge, should weaken or even reverse the radial magnetic field gradient in the inner disk region, while leaving the disk cool enough (in the absence of turbulence) to keep $\beta \leq 1$. It could thus make both the AEI and MRI stable, leading to state *A*. Accretion proceeding from the outer part of the disk, and gradually refilling the inner disk with weakly magnetized gas, would after some time allow the observed return to state *B*. Figure 3 sketches the corresponding profiles of β in Belloni’s three basic states, in the inner disk region.

This immediately leads to a possible explanation for the striking observation of Belloni *et al.* (2000), that all transitions between their basic states are seen *except* the transition from state *C* to *B*: in our scenario, state *C* means that the disk has accumulated a critical amount of vertical magnetic flux in its inner region. Once it is in that state, it can decrease its magnetization *only* by a reconnection event, leading to state *A*. Then accretion from the outer regions replenishes the inner disk with low magnetization material, allowing the MRI-unstable region to progress inward until it reaches the inner disk edge, seen as a return to state *B*. This would then explain the smooth transition observed from state *A* to *B*, in contrast with the sharp transitions from *C* to *A* (due to reconnection) and from *B* to *C*: there, as discussed in section 4.2, the transition is sharp because as β falls below 1, the MRI stops, so that the disk cools down, further decreasing β .

This has then suggested us to seek an interpretation for the LFQPO sometimes seen during short dips occurring while the source is in the ‘high/soft’ state. This is dis-

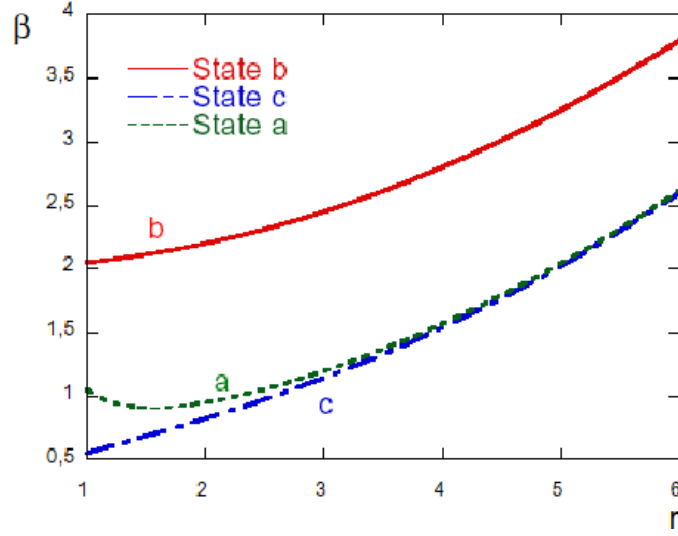


FIG. 3.— The radial profile of $\beta = 8\pi p/B^2$ in Belloni's three basic states, as predicted in our scenario. In state *B* the source is weakly magnetized, and in a classical 'high-soft' state. In state *C* it is more strongly magnetized and subject to the AEI, producing the LFQPO and leading to a 'low-hard' state. In state *A* reconnection has weakened the magnetic field in the inner disk region, keeping $\beta < 1$ but with a profile immune to the AEI.

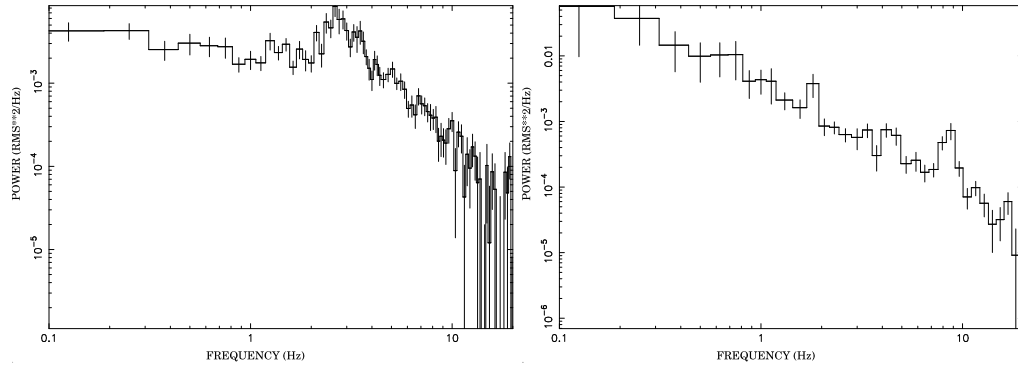


FIG. 4.— Power Density Spectra taken while the source is in state *C*. Upper panel: PDS taken at the bottom of the long dip (about 236 s duration) of figure 2, while the source is already in the *C* (hard) state. Bottom panel: PDS taken during an entire short dip (53 s duration) where the source briefly transits to state *C* while it is generally in the high oscillation phase.

cussed and shown in particular in figure 1 of Markwardt *et al.* (1999): they find that the high state of a class β cycle is interrupted by such dips, where the source is in a spectral state similar to the long dips (this, shown by black intervals in the center bar of their figure, must thus be state C), and the LFQPO appears. Following our scenario, this occurs at times where the radial profile of B still leaves $\beta > 1$, while magnetic flux is slowly accreted to the inner disk region. A possible explanation, following our scenario, would be that at these times β in the inner disk is not much larger than one, so that the AEI can appear but that these episodes remain transient until a necessary condition is met to let the long dips occur. This condition would then certainly concern the global magnetic field profile, allowing during the low state the outward motion of the inner disk edge which characterizes the long dips.

Seeking an indication in favor of this explanation, we have examined the Power Density Spectrum of the source, comparing a short dip and a long one. The results are shown in figure 4. The first spectrum, obtained near the minimum of the long dip of figure 2, shows the characteristic aspect with band-limited noise at low frequencies, a break, and the QPO (here near 3 Hz). The second spectrum is taken during the short dip shown at time $\sim 2450 - 2500$ in figure 1 of Markwardt *et al.* (1999), and is indeed very different: it shows a power-law spectrum, as usually found in the low-high state (state B), to which the QPO is superimposed near 9 Hz. We would expect the break at a frequency higher than 1 Hz, while the interval analyzed is 53 seconds long so that, although the disk properties are more transient here than during the long dip, we believe that this is not due to the limited time window. On the other hand interpretation is difficult, since the disk emission is more present here than during the long dip (as the disk is hotter). However, and although this would need to be analyzed in more details over a number of occurrences, it might thus indicate that these occurrences of state C are in fact slightly different; in our interpretation, during the short dip the formation of the QPO does not manage to quench the MRI turbulence associated with the power-law PDS, characteristic of the high/soft state.

4.4. The central magnetic structure

Reconnection at the inner edge of the disk is the best explanation for the spike leading to the relativistic ejections; it would merge magnetic field lines from the disk and field lines from the central magnetic structure surrounding the black hole. We consider here the same magnetic structure involved in the Blandford-Znajek process (Blandford and Znajek 1977), whether or not this process is efficient enough to generate a jet, in its force-free initial form or in more elaborate ones such as used by Eikenberry and Van Putten (2003). Their model of the global magnetic configuration, involving opposite current loops in a torus around the black hole, is not unique and different from ours where the disk is threaded by open field lines. One might probably, rather than reconnection, find alternative explanations based on other types of large-scale magnetic events, but reconnection is clearly the first possibility to consider. However for this to occur the poloidal magnetic flux accreted with the gas and the one trapped in the central magnetic structure, in the inner hole surrounding the

central object, must have opposite signs.

This would mean that the classes of variability where ejections occur can happen only when the poloidal fluxes in the disk and this structure are antiparallel, and thus that during certain periods the source is in that configuration, while during other periods the fluxes have the same sign. This would lead to a dichotomy, similar to the one observed at the interface between the terrestrial magnetic field and the one carried by the solar wind: it is only when these fields are antiparallel that reconnection is observed, while in the parallel configuration more complex behaviors occur.

Thus, although it may seem to be a far-fetched assumption for the interface between the disk and the central magnetic structure, it is hard to escape if reconnection is involved. One also has to remember that the central magnetic structure is not anchored in the black hole, but in a current ring at the inner edge of the disk; the poloidal flux it contains is thus not a constant, as in neutron stars whose flux can vary only over very long periods. Here the trapped flux is the sum of all the magnetic flux accreted during the whole history of the source, while the gas itself will end up in the black hole.

On the other hand, the flux advected with the gas may also change over time: as discussed in section 4.1, this flux may have its origin either in the companion star the gas comes from, or in a turbulent dynamo in the disk. In both cases the sign of this flux is expected to vary, although the characteristic time scale of this variation is difficult to assess (there is for instance still no quantitative explanation for the duration of the 22-year cycle of the Sun, associated with such field reversals, and convection must be much more complex in a companion star stirred by tidal effects). We will discuss below how the time scale observed in GRS 1915+105, which we would associate with this long-term evolution, is of the order of one to a few years. This is certainly not unreasonable for either process.

Thus the processing of magnetic flux in the disk and the central magnetic structure would be responsible for two time scales: a short one, responsible for the ~ 30 minutes cycles, corresponding to the accumulation and release of magnetic flux in the inner region of the disk; and a much longer one, corresponding to changes in the sign of the flux advected with the disk, and due to changes at the source of this flux, be it a dynamo in the disk itself or the companion star.

4.5. Long-term behavior

That there is an unknown parameter, besides the accretion rate, regulating the long-term behavior of GRS 1915+105 has long been suspected; from a statistical analysis Greenhough *et al.* (2003) have found a 12-17 days time scale which might be associated with the orbital motion of the binary. More recently Rau *et al.* (2003) found in its hard X-ray and radio fluxes a 590 days period. Their preferred explanation involves the precession of a warp in the disk, but it they find it difficult in this context to understand that this periodicity is seen in the coronal emission only and not in the soft X-ray flux from the disk. We will first note here that a turbulent dynamo model would appear as a better candidate since the mag-

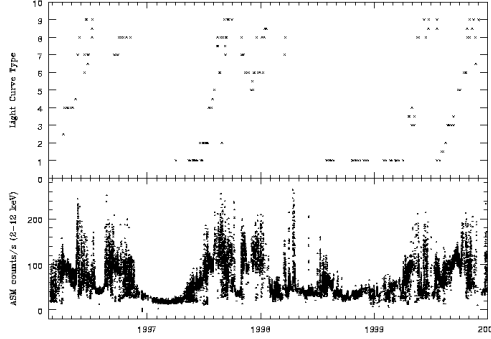


FIG. 5.— This figure, reproduced from Fitzgibbon *et al.* (2000), shows: lower plot, the X-ray light curve of GRS 1915+105 during the period studied; upper plot, the history of the source in terms of their classes of variability. Each class corresponds to a type of variability of the source, in a manner similar to Belloni *et al.* (2000). Clearly they occur in a well-defined and repetitive order.

netic field in the disk directly affects dissipation in the corona. As mentioned in section 4.4, such a period would not be unrealistic for field reversals in the disk or even in the companion star.

However we also wish to mention unpublished work by Fitzgibbon *et al.* (2000), which also indicates order in the long-time variability of GRS 1915+105, including its disk emission: examining over 350 RXTE observations of GRS 1915+105 between 1996 and 1999, they first defined nine basic classes of variability of GRS 1915+105, analogous (and generally similar) to the twelve ones independently found by Belloni *et al.* (2000); they ordered these classes (numbered 1 to 9) by various criteria, the main one being the direct observation of transitions between two classes. Then they plotted, over this period of nearly four years, the observed class of variability. Their result, reproduced in figure 5, shows that the source follows a regular pattern, going from class 1 to class 9 before it returns to a steady state (not included among the nine classes, and not shown in figure 5). Then after some time it starts over at class 1. They also find that there is no strong correlation between this and the total flux of the source. We cannot reproduce here their analysis, which would deserve to be repeated in more details and in terms of the 12 classes of Belloni *et al.* (2000), since they have become the standard description for the variability of GRS 1915+105; a comparison between this and the periodicity of Rau *et al.* (2003) would also of course be necessary. We will only note that these classes are very similar to Belloni's, and that the ~ 30 minutes cycle (class β) is their class 8. Our main interest here is the quite unexpected existence of such a regularity in the long-term behaviour of GRS 1915+105, which must be considered as an outstanding challenge to any model of accretion in this source.

In section 4.4 we concluded that, if reconnection events are involved in the spike of the ~ 30 minutes cycles and in the relativistic ejections, this is most likely to occur during periods where the poloidal fluxes in the disk and the central hole have opposite signs; we must then expect the source to be in this configuration (antiparallel vertical fields) part of the time, and in the opposite one (with parallel fields) at other times. Changing from one configuration to the other requires a change in the sign of either the magnetic flux advected with the gas in the disk, or the total flux trapped in the central magnetic structure.

A change in the sign of the advected magnetic flux may result from a field reversal in the dynamo generating the advected flux, in the companion star or in the disk itself. Field reversals are to be expected in turbulent dynamos, but not much is known about their characteristic time scale. The orientation of the magnetic field should not affect the main body of the disk (weakly magnetized anyway); on the other hand it should strongly affect the interaction with the central magnetic structure, and thus the accretion process in the inner region of the disk. On the long term, a sufficient number of reconnection events might eventually cancel the trapped flux, and change its sign.

Since we are elaborating on a model of the cycles, which is itself an extrapolation of our candidate for the low-frequency QPO, we will not try to go further in this direction. We however consider very possible that the long-term evolution seen in figure 5 could result from the processing of poloidal magnetic flux in the disk and the central magnetic structure.

5. DISCUSSION

In this paper we have started by presenting our model for the Low-Frequency Quasi-Periodic Oscillation of X-ray binaries, particularly the microquasar GRS 1915+105, based on the Accretion-Ejection Instability predicted to occur in the inner region of magnetized disks. Assuming that the AEI does explain the LFQPO, we have then proceeded by extrapolation, seeking in the properties of the instability an explanation for the observed behavior of the source.

This has allowed us to build up a scenario for the ~ 30 minutes cycles (Belloni's class β) of GRS 1915+105. We call this a 'Magnetic Flood' model, because it explains the cycles by the gradual accumulation of magnetic flux in the inner region of the disk, and sudden release in reconnection events producing the relativistic ejections. The scenario is consistent with both the observations and the physical properties of the instability, *i.e.* its instability conditions, and its transport of accretion energy outward and to the corona (so that the disk cools down and the corona is energized when the AEI is present). This allows us to find a natural explanation for the observation that the apparition of the QPO occurs *just before* the transition to the low state, so that the QPO may *cause* the transition,

rather than be its consequence.

Turning to the reduction, by Belloni *et al.* (2000), of the variability of GRS 1915+105 to 12 classes and then to 3 basic states, *A*, *B* and *C*, we then identify these states of the inner disk region as

state *B* : a standard, weakly magnetized disk ($\beta > 1$) subject to the Magneto-Rotational Instability; the local deposition of accretion energy heats the disk resulting in a high-soft state

state *C* : a more (though moderately) magnetized state, where the poloidal field has become of the order of equipartition with the gas pressure ($\beta \lesssim 1$); in this state the MRI is stabilized and the AEI unstable, producing the LFQPO, reducing the disk heating and exciting the corona where a part of the accretion energy is transported

state *A* : a state which is still moderately magnetized ($\beta \lesssim 1$, preventing the MRI) but where magnetic flux near the inner edge of the disk has been destroyed in the reconnection; the resulting magnetic field profile does not allow the AEI to be unstable, so that the inner disk is essentially calm until accretion proceeding from larger radii increases β and allows a return to state *B*.

This allows us to give a possible explanation for the observation of Belloni *et al.* (2000) that a direct transition from state *C* to state *B* is never observed: magnetic flux has to be destroyed, leading to state *A*, before accretion of gas from larger radii allows a return to state *B*.

We have then explored how this could allow a further extrapolation, to the other classes of variability of GRS 1915+105 and its behavior on longer time scales. For this we started from the conclusion of our model, that the source must be part of the time in a configuration where the vertical magnetic flux in the disk and the one trapped in the central structure surrounding the black hole are parallel, while at other times they are antiparallel. This is in fact unescapable if the relativistic ejections are due to a large scale reconnection event between the disk and the central magnetic structure. We confronted this with the unpublished work of Fitzgibbon *et al.* (2000), which shows a surprising regularity in the manner GRS 1915+105 explores its different classes of variability. We are led to suggest that this regularity in the long-term evolution is ruled by reversals in the sign of the magnetic flux advected to the inner disk region. This flux may result from a dynamo in the companion star or in the disk itself, and is eventually accreted to the central magnetic structure, which may thus also reverse its sign periodically.

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